STATE OF HAWAII
DEPARTMENT OF LAND AND NATURAL RESOURCES
COMMISSION ON WATER RESOURCE MANAGEMENT
P.O. BOX 621
HONOLULU, HAWAII 96809

STAFF SUBMITTAL

for the meeting of the
COMMISSION ON WATER RESOURCE MANAGEMENT

March 16, 2011
Honolulu, Oahu

Request to Authorize the Chairperson to Enter into an Agreement with U.S. Geological Survey to Update Estimated Groundwater Recharge Distribution, Island of Oahu, Hawaii

SUMMARY OF REQUEST:

Staff requests the Commission on Water Resource Management (Commission) authorize the Chairperson to enter into an agreement with the U.S. Geological Survey (USGS) to update estimated ground water recharge distribution for the island of Oahu.

BACKGROUND:

The State Water Code requires the Commission to establish hydrologic units and their sustainable yields in the Water Resource Protection Plan component of the Hawaii Water Plan to ensure the long-term protection and responsible management of Hawaii's ground water resources. Sustainable yield is defined as "the maximum rate at which water may be withdrawn from a water source without impairing the utility or quality of the water source as determined by the commission". Haw. Rev. Stat. §174C-31(i)(2)

The initial Water Resource Protection Plan, adopted by the Commission in 1990 (and updated in 2008), established ground water hydrologic units and their sustainable yields. However, the determination of sustainable yield is based on best available information. As new and better data become available, the Commission must periodically review and refine estimates of sustainable yield.

In setting sustainable yields, the Commission must first assess the quantity of ground water recharge to the aquifer. Ground water recharge is the replenishment of fresh ground water and depends on many natural and human-related factors. Recharge can change over time in response to changes and events in climatological trends and land use.

An updated island-wide estimate of recharge distribution is needed for the island of Oahu. Recharge for Oahu was last evaluated in 1996. That study relied on even older publications. Since then, there have been significant improvements in modeling tools and methodology for estimating recharge. There have also been significant changes in land and water use, in particular the cessation of plantation agriculture and an increase in the urbanization of former agricultural lands and other previously-undeveloped lands. Such large-scale land and water use changes can greatly affect water budgets.

In addition, hydrological data collection and analysis indicate that Hawaii's climate is changing. USGS reviewed daily mean discharge data at seven of its long-term-trend stations in Hawaii from 1913 to 2002. The study found statistically significant downward trends in annual base flow during the study period at all seven stations. This finding corresponds to independent research on rainfall by the University of Hawaii that also documented downward trends in rainfall during this period. Studies have also shown that while overall rainfall has declined, rainfall intensity and air temperatures have increased.

While further research is needed to determine whether the downward trends in rainfall and streamflow continue or are part of a long-term cycle, any changes in rainfall, streamflow, and air temperature, will have significant impacts on ground water recharge and sustainable yields. It is imperative that the Commission review and refine recharge and sustainable yield estimates as ground water accounts for over 90% of our State's drinking water supplies. The Commission's 2008 Water Resource Protection Plan identified improvement of recharge estimates as a key priority.

In 2008, the Commission approved a contract to update the Rainfall Atlas of Hawaii. It has not been updated since 1983. Almost thirty (30) years of updated rainfall data will be available to refine ground water recharge and sustainable yield estimates.

Last month, Honolulu Board of Water Supply (BWS) entered into a contract with USGS to refine recharge estimates for the Pearl Harbor Aquifer Sector Area and develop a numerical ground water model of the Pearl Harbor area. The subject island-wide recharge study will complement the BWS/USGS study by completing the re-evaluation of recharge for the rest of the island using a consistent and refined methodology.

SCOPE OF SERVICES:

The proposed work calls for a 1.5-year study to estimate the spatial distribution of ground water recharge for the island of Oahu (Exhibit 1). The Commission will use the results to review and update sustainable yield estimates for Oahu aquifers. This study will refine a USGS numerical ground water model as part of a separately funded study between the USGS and BWS. (While the Commission is not funding this separate study, the Commission will directly benefit from it by gaining an improved understanding of how ground water withdrawals affect the resource.)

The work will aggregate daily recharge estimates for current average climatic conditions and land use for each month of the year. Historic recharge will be estimated for 10-year intervals, (beginning about 1900) using land use and rainfall representative of each time period. Several other scenarios will be examined, including possible future land use, drought, and effects of climate change. Results from this study will be published in the USGS Scientific Investigations Report series and made available on the internet.

The total cost of this agreement will be $165,000. The Commission's share will be $100,000. USGS will provide the remaining $65,000.

USGS and BWS entered into a separate agreement to develop recharge distributions and refine a numerical model for the Pearl Harbor area. For the recharge portion, the USGS/BWS agreement establishes the cost-share: BWS pays $40,750; USGS pays $19,250.

The total cost to complete the recharge assessment for the entire island of Oahu is $225,000. CWRM ($100,000) and USGS ($65,000) will pay $165,000 for one portion. BWS ($40,750) and USGS ($19,250) will pay $60,000 for the second portion. This breakdown is based on the relative size of the Pearl Harbor area which account for about 26% of the island or approximately $60,000 of the total cost.

FUNDING:

Staff requests the Commission approve $100,000 to complete the Oahu recharge study. Funding will be from the Commissions general fund, special fund, or a combination of both, subject to available funding. Staff may also receive funding contributions from key agencies, organizations, stakeholders or partners.

ENVIRONMENTAL REVIEW (CHAPTER 343, HRS)

HRS Chapter 343 does not apply because this is a planning study. Administrative Rule 11-200-5(d) provides:

"*For agency actions, chapter 343, HRS, exempts from applicability any feasibility or planning study for possible future programs which the agency has not approved, adopted, or funded. Nevertheless, if an agency is studying the feasibility of a proposal, it shall consider environmental factors and available alternatives and disclose these in any future assessment or subsequent statement. If, however, the planning and feasibility studies involve testing or other actions which may have significant impact on the environment, then an environmental assessment shall be prepared.*"

The proposed Oahu Recharge Study is a planning study, which does not involve testing or other actions that will impact the environment. Therefore, HRS Chapter 343 is not applicable to this agency action.

RECOMMENDATION

Staff recommends that the Commission:

1. Authorize the Chairperson to enter into an agreement between the Commission and the U.S. Geological Survey to update ground water recharge distribution estimates for the Island of Oahu and to approve funding not to exceed $100,000 to complete the study. Commission funding will be from general funds or special funds or a combination of both, subject to the availability of funding.

2. Authorize the Chairperson to amend or modify the joint funding agreement provided that such amendment or modification does not include any additional funding.

The terms of this agreement will be subject to the approval of the Chairperson and the Department's Deputy Attorney General.

Respectfully submitted,

WILLIAM M. TAM
Deputy Director

Exhibit 1 USGS Scope of Investigations for Spatial Distribution of Groundwater Recharge, Island of Oahu, Hawaii

APPROVED FOR SUBMITTAL:

WILLIAM J. AILA, JR.
Chairperson

Attachment 1

SCOPE OF INVESTIGATIONS

SPATIAL DISTRIBUTION OF GROUNDWATER RECHARGE, ISLAND OF OAHU, HAWAII

U.S. Geological Survey
Pacific Islands Water Science Center

SUMMARY

An updated, island-wide estimate of groundwater-recharge distribution is needed for the island of Oahu, Hawaii (fig.1). Published 15 years ago, the last island-wide estimate of groundwater-recharge distribution was presented in Shade and Nichols (1996), which relied heavily on even older publications. In addition to advanced computing power and improved geographic information systems (GIS), current water-budget models for the estimation of recharge in the Hawaiian Islands use estimates of fog interception, estimates of canopy evaporation, and updated soil and land-cover maps that were not used in water-budget models prior to the 21st century. A new water-budget model for Oahu also would take into account the substantial changes in urban and agricultural land use that have occurred during the last several decades, as well as project the effects of future land-use and climate changes.

Updated recharge estimates for Oahu are recommended in the Water Resource Protection Plan (WRPP) (State of Hawaii, 2008). CWRM periodically reassesses sustainable yields as updated recharge values and related information become available. Although pumpage from each aquifer system on Oahu was within the sustainable yield as of 2008 (State of Hawaii, 2008), demand for groundwater is growing. CWRM projects that island-wide groundwater withdrawals will increase from an estimated 164 million gallons per day (Mgal/d) in 2010 to 206 Mgal/d in 2030, a rise of about 26 percent (State of Hawaii, 2008).

Estimates of past, present, and future groundwater recharge are needed to refine an existing USGS three-dimensional numerical groundwater model of the Pearl Harbor aquifer. The Pearl Harbor aquifer (fig. 1) is the most important aquifer on the island of Oahu and currently supplies about 100 Mgal/d of fresh groundwater mainly for public supply. Decisions related to future infrastructure development and alternate sources of fresh water, including desalinization, will depend on the long-term sustainability of the groundwater resources in the Pearl Harbor aquifer.

The objective of this study is to estimate the spatial distribution of groundwater recharge on the island of Oahu. Results from this study can be used to update sustainable-yield estimates and will be used to refine the USGS numerical groundwater model of the Pearl Harbor aquifer. Past recharge will be estimated for 10-year intervals, beginning in about 1900, using land use and rainfall representative of each time period. Several other scenarios will also be examined, including possible future land use, drought, and effects of climate change. The study will include the modification of an existing daily water-budget model and the preparation of existing climatic, land use, land cover, soil, and streamflow data necessary to execute the water-budget model. Results of the study will be made available to the public in a USGS Scientific Investigations Report. It is anticipated that the work will take 1.5 years from the time work is commenced until the report is published and will cost $225,000.

PROBLEM

An updated, island-wide estimate of groundwater-recharge distribution is needed for the Island of Oahu, Hawaii (fig.1). Published 15 years ago, the last island-wide estimate of groundwater-recharge distribution was presented in Shade and Nichols (1996), which relied heavily on even older publications that calculated water budgets for southern (Giambelluca, 1983) and southeastern (Eyre and others, 1986) Oahu. In addition to advanced computing power and improved geographic information systems (GIS), current water-budget models for the estimation of recharge in the Hawaiian Islands use estimates of fog interception, estimates of canopy evaporation, and updated soil and land-cover maps that were not used in water-budget models prior to the 21st century (see for example, Izuka and others, 2005; Engott and Vana, 2007). A new water-budget model for Oahu also would take into account the substantial changes in urban and agricultural land use that have occurred during the last several decades, as well as project the effects of future land-use and climate changes.

Updated recharge estimates for Oahu are recommended in the Water Resource Protection Plan (WRPP) (State of Hawaii, 2008). Estimates of recharge are used by the State Commission on Water Resource Management (CWRM) to set sustainable yields for aquifer systems on the island. CWRM periodically reassesses sustainable yields as updated recharge values and related information become available. Although pumpage from each aquifer system on Oahu was within the sustainable yield as of 2008 (State of Hawaii, 2008), demand for groundwater is growing. CWRM projects that island-wide groundwater withdrawals will increase from an estimated 164 million gallons per day (Mgal/d) in 2010 to 206 Mgal/d in 2030, a rise of about 26 percent (State of Hawaii, 2008).

Estimates of past, present, and future groundwater recharge are needed to refine a USGS three-dimensional numerical groundwater model of the Pearl Harbor aquifer (Oki, 2006). The Pearl Harbor aquifer (fig. 1) is the most important aquifer on the island of Oahu and currently supplies about 100 Mgal/d of fresh groundwater mainly for public-supply. Chloride concentrations of water pumped by some wells in the eastern part of the Pearl Harbor aquifer have risen in recent years, although recent pumpage from the area is near the CWRM-estimated sustainable yield for the area. Decisions related to future infrastructure development and alternate sources of fresh water, including desalinization, will depend on the long-term sustainability of the groundwater resources in the Pearl Harbor aquifer.

Description of Study Area

The study area encompasses the entire island of Oahu (fig. 1), covering 604 square miles. Oahu is the third largest of the Hawaiian Islands and most populous, with a population of 905,034 in 2009 (State of Hawaii, 2009). Oahu is the center of commerce, industry, and government in Hawaii and is the site of the State capital, Honolulu. The following description is modified from Nichols and others (1996).

Physical Setting—Oahu is formed by the eroded remnants of two elongated shield volcanoes with broad, low profiles. Weathering and erosion have modified the original domed surfaces of the volcanoes, leaving a landscape of deep valleys and steep inter-fluvial ridges in the interior highlands. The Koolau Range in eastern Oahu and the Waianae Range in western Oahu are the eroded remnants of the Koolau and Waianae Volcanoes. In central Oahu, which forms the saddle between the Koolau and Waianae Ranges, erosion has been less severe and has modified the original domes only slightly.

A flat coastal plain composed of sedimentary deposits, referred to as caprock, surrounds much of Oahu. The caprock varies in width from a narrow marine terrace to a broad plain several miles wide. Where it is extensive, such as in southern Oahu, its surface is composed mainly of emerged Pleistocene reefs and associated sediments.

Streams on Oahu are short, with steep gradients and small drainage areas. Main courses of streams generally follow the consequent drainage pattern established on the original domed surfaces of the shield volcanoes. Lower-order tributaries branch off from the main courses in a dendritic pattern. Steep terrain and steep stream gradients cause water to run off rapidly following precipitation. As a result, streamflow is characteristically flashy, with high flood peaks and commonly little base flow. Few streams are perennial over their entire reach. Streamflow is perennial at high altitudes where precipitation is persistent and near sea level where streams intercept shallow groundwater. These conditions virtually preclude surface-water development on Oahu and lead to heavy reliance on groundwater.

Climate—The subtropical climate of Oahu is characterized by mild temperatures, moderate to high humidity, prevailing northeasterly tradewinds, and extreme variation in precipitation over short distances. Climate varies spatially with altitude and in relation to prevailing and local winds.

A pronounced orographic pattern of cloud cover and precipitation is established as moist oceanic air is forced up and over the mountainous terrain of Oahu by persistent tradewinds. Mean annual precipitation has a steep orographic gradient and varies widely, ranging from less than 40 to about 60 inches per year (in/yr) on the northern and windward (northeastern) coast, to about 275 in/yr near the crest of the Koolau range, to less than 25 in/yr over the leeward (southwestern) lowlands (Giambelluca and others, 1983). The Waianae Range lies in the trade-wind rainshadow of the Koolau Range and receives much less precipitation, with a maximum of about 80 in/yr falling on the Waianae summit. Mean annual precipitation over the open ocean near Oahu is about 25 in. (Blumenstock and Price, 1967).

Precipitation over much of Oahu is markedly seasonal. In lowland and coastal areas, the wetter winter months, October through April, receive about 70 percent of the total annual precipitation. Mountainous areas, particularly the Koolau range, receive a fairly steady contribution of trade-wind precipitation that is supplemented by intense, episodic rains from hurricanes, winter cold fronts, and convective disturbances associated with low pressure in the upper atmosphere.

Geology and Hydrogeology—The geology and hydrogeology of Oahu have been much studied (for example, Stearns and Vaksvik, 1935; Visher and Mink, 1964; Takasaki and others, 1969; Macdonald and others, 1983; Hunt, 1996).

OBJECTIVE

The objective of this study is to estimate the spatial distribution of groundwater recharge on the island of Oahu. Daily recharge estimates for current average climatic conditions and land use will be aggregated for each month of the year. Past recharge will be estimated for 10-year intervals, beginning in about 1900, using land use and rainfall representative of each time period. Several other scenarios will also be examined, including possible future land use, drought, and effects of climate change. The study will include the modification of an existing daily water-budget model and the preparation of existing climatic, land use, land cover, soil, and streamflow data necessary to execute the water-budget model. Results of the study will be made available to the public in a USGS Scientific Investigations Report posted on the Pacific Islands Water Science Center website. The report will document the recharge by State aquifer system.

APPROACH

A GIS-based water-budget model will be developed for this study to estimate the spatial distribution recharge (see for example, Izuka and others, 2005; Engott and Vana, 2007). For this study, a daily time step will be used to avoid possible biases associated monthly or annual time steps (Giambelluca and Oki, 1987). Daily recharge estimates for current average climatic conditions and land use will be aggregated for each month of the year. Past recharge will be estimated for 10-year intervals, beginning in about 1900, using land use and rainfall representative of each time period. Several other scenarios will also be examined, including possible future land use, drought, and effects of climate change. The accuracy of recharge estimates from the water-budget model is limited by the accuracy of the input data. Sensitivity of recharge estimates to model input will be quantified.

Water-Budget Calculations

Groundwater recharge for the island of Oahu will be computed using the daily water-budget model and input data that quantify the spatial and temporal distribution of rainfall, fog interception, irrigation, evaporation, runoff, soil type, and land cover. Figure 2 shows the generalized water-budget flow diagram. Areas of homogeneous properties, termed "subareas", are generated by merging datasets that characterize the spatial and temporal distribution of rainfall, fog, irrigation, pan evaporation, runoff, soil type, and land cover in a geographical information system (GIS). For each subarea, recharge is calculated by the water-budget model. At the end of a simulation period, results for the subareas are summed over larger areas of interest, which can include entire aquifer systems.

For each subarea at the start of each day, the model calculates an interim moisture storage. Interim moisture storage is the amount of water that enters the plant-root zone for the current day plus the amount of water already in the zone from the previous day. For non-forest subareas, it is given by the equation:

$$X_i = P_i + F_i + I_i + W_i - R_i + S_{i-1}, \tag{1a}$$

where:

X_i	=	interim moisture storage for current day [L],
P_i	=	rainfall for current day [L],
F_i	=	fog interception for current day [L],
I_i	=	irrigation for current day [L],
W_i	=	excess water from the impervious fraction of an urban area distributed over the pervious fraction [L],
R_i	=	runoff for current day [L],
S_{i-1}	=	moisture storage at the end of previous day (i-1) [L], and
i	=	subscript designating current day.

For forest subareas, interim moisture storage is given by the equation:

$$X_i = (NP)_i - R_i + S_{i-1}, \tag{1b}$$

where:

$(NP)_i$ = net precipitation for current day [L],

For forest subareas, net precipitation is computed as the sum of rainfall and fog interception less canopy evaporation, which is the amount of water from rainfall and fog that collects on the leaves, stems, and trunks of trees and subsequently evaporates. The equation is:

$$(NP)_i = P_i + F_i - (CE)_i, \qquad (2)$$

where:

$(CE)_i$ = canopy evaporation [L]

For urbanized subareas, the interim equation includes the factor W_i, which pertains to the fraction of urban subareas that are estimated to be impervious (see eq. 1a). In non-urban subareas where there is no impervious fraction, W_i is zero. Urbanized subareas are assigned a fraction (z) that is impervious. This fraction is used to separate, from the total rain that falls in an urbanized subarea, a depth of water that is treated computationally as though it fell on an impervious surface. Based on this impervious water fraction, some water is subtracted to account for direct evaporation. The remainder of the water (W_i) is added to the water budget of the pervious fraction of the model subarea. Thus, for the pervious fraction of an urban subarea, the total daily water input includes an excess of water from the impervious fraction.

For an urbanized model subarea, excess water, W_i, and water storage (ponded water) on the surface of impervious areas were determined using the following conditions:

$$X1_i = P_i - R_i + T_{i-1}, \qquad (3)$$

for $X1_i \leq N$, $\quad W_i = 0$, and

$$X2_i = X1_i,$$

for $X1_i > N$, $\quad W_i = (X1_i - N)z \,/\, (1\text{-}z)$, and

$$X2_i = N, \qquad (4)$$

where:

$X1_i$ = first interim moisture storage on the surface of impervious area for current day [L],

$X2_i$ = second interim moisture storage on the surface of impervious area for current day [L],

T_{i-1} = water storage (ponded water) on the surface of impervious area at the end of the previous day (i-1) [L],

N = rainfall interception capacity (maximum amount of water storage on the surface of impervious area) [L], and

z = fraction of area that is impervious [dimensionless].

The water storage on the surface of the impervious area at the end of the current day, T_i, is determined from the equation:

for $X2_i > V_i$, $\quad T_i = X2_i - V_i$, and

$$\text{for } X2_i \leq V_i, \quad T_i = 0, \tag{5}$$

where:

V_i = pan evaporation for current day [L].

The next step in the water-budget computation is to determine the amount of water that will be removed from the plant-root zone by ET. Actual ET is a function of potential ET and interim moisture (X_i). A vegetated surface loses water to the atmosphere at the potential-ET rate if sufficient water is available. At all sites, potential ET is assumed to be equal to pan evaporation multiplied by an appropriate vegetation factor, termed a pan coefficient. For moisture contents greater than or equal to a threshold value, C_i, the rate of ET is assumed to be equal to the potential-ET rate. For moisture contents less than C_i, the rate of ET is assumed to occur at a reduced rate that declines linearly with soil-moisture content:

$$\begin{aligned} &\text{for } S \geq C_i, && E = (PE)_i\text{, and} \\ &\text{for } S < C_i \text{ and } C_i > 0 && E = S \times (PE)_i / C_i \end{aligned} \tag{6}$$

where:

E = instantaneous rate of evapotranspiration [L/T],

$(PE)_i$ = potential-evapotranspiration rate for the current day [L/T],

S = instantaneous moisture storage [L], and

C_i = threshold moisture storage for the current day below which evapotranspiration is less than the potential evapotranspiration rate [L].

The threshold moisture storage, C_i, is estimated using the model of Allen and others (1998) for soil moisture. In this model, a depletion fraction, p, which ranges from 0 to 1, is defined as the fraction of maximum moisture storage that can be depleted from the root zone before moisture stress causes a reduction in ET. The threshold moisture, C_i, is estimated from p by the equation:

$$C_i = (1 - p) \times S_m , \tag{7}$$

where:

S_m = moisture-storage capacity of the plant-root zone [L].

The moisture-storage capacity of the plant-root zone, S_m, expressed as a depth of water, is equal to the plant root depth multiplied by the available water capacity of the soil, ϕ. Available water capacity is the difference between the volumetric field-capacity moisture content and the volumetric wilting-point moisture content:

$$S_m = D \times \phi , \tag{8}$$

where:

D	=	plant root depth [L],
ϕ	=	θ_{fc} - θ_{wp} [L^3/L^3],
θ_{fc}	=	volumetric field-capacity moisture content [L^3/L^3], and
θ_{wp}	=	volumetric wilting-point moisture content [L^3/L^3].

Values for p depend on vegetation type and can be adjusted to reflect different potential-ET rates. In the water-budget model, the ET rate from the plant-root zone may be (1) equal to the potential-ET rate for part of the day and less than the potential-ET rate for the remainder of the day, (2) equal to the potential-ET rate for the entire day, or (3) less than the potential-ET rate for the entire day. The total ET from the plant-root zone during a day is a function of the potential-ET rate ($(PE)_i$), interim moisture storage (X_i), and threshold moisture content (C_i). By recognizing that $E = -dS/dt$, the total depth of water removed by ET during a day, E_i, is determined as follows:

for $X_i > C_i$ and $C_i > 0$,

$$E_i = (PE)_i t_i + C_i\{1\text{-}\exp[-(PE)_i(1\text{-}t_i)/C_i]\},$$

for $X_i > C_i$ and $C_i = 0$,

$$E_i = (PE)_i t_i,$$

for $X_i \leq C_i$ and $C_i > 0$,

$$E_i = X_i\{1\text{-}\exp[-(PE)_i / C_i]\},$$

and

for $X_i = C_i$, and $C_i = 0$,

$$E_i = 0, \qquad (9)$$

where:

E_i = evapotranspiration from plant-root zone during the day [L],

t_i = time during which moisture storage is above C_i [T]. It ranges from 0 to 1 day and is computed as follows:

for $(X_i - C_i) < (PE)_i(1 \text{ day})$

$$t_i = (X_i - C_i)/(PE)_i,$$

and

for $(X_i - C_i) \geq (PE)_i(1 \text{ day})$,

$$t_i = 1. \tag{10}$$

After accounting for runoff (eq. 1a or 1b), ET from the plant-root zone for a given day is subtracted from the interim moisture storage, and any moisture remaining above the maximum moisture storage is assumed to be recharge. The daily rate of direct recharge from anthropogenic sources is also added to daily recharge at this point. Recharge and moisture storage at the end of a given day are assigned according to the following conditions:

for X_i-$E_i \leq S_m$, $Q_i = DR$, and

$S_i = X_i$-E_i ,

and

for X_i-$E_i > S_m$, $Q_i = (X_i$-E_i-$S_m) + DR$, and

$$S_i = S_m , \tag{11}$$

where:

Q_i = groundwater recharge during the day [L], and

S_i = moisture storage at the end of the current day (i) [L],

DR = daily rate of direct recharge from anthropogenic sources [L] (water-main leaks, cesspool discharge, etc.).

Moisture storage at the end of the current day, expressed as a depth of water, is equal to the root depth multiplied by the difference between the volumetric soil-moisture content within the root zone at the end of the current day, and the volumetric wilting-point moisture content.

$$S_i = D \times (\theta_i - \theta_{wp}), \qquad (12)$$

where:

θ_i = volumetric soil-moisture content at the end of the current day, i, $[L^3/L^3]$.

REPORT

The anticipated product of this study is a report in the USGS Scientific Investigations Report series. The report will be made available through the Internet. The probable report title, report outlet, and milestone dates are listed in table 1.

Table 1. Milestone dates for planned report

Probable title	Report outlet	First draft	Review	Approval	Publication
Spatial Distribution of Groundwater Recharge on the Island of Oahu, Hawaii	USGS SIR	3/2012	5/2012	8/2012	09/2012

BUDGET

A total of about $225,000 is needed for the 1-1/2 year study. A cost breakdown is provided in table 2. Labor includes salary and indirect costs for leave, facilities, and overhead assessments. Science support includes indirect costs for project management, technical services, and report processing fees.

Table 2. Cost breakdown.

Category	**Amount**
Labor	$201,850
Report Printing	$700
Science Support	$22,450
Total	**$225,000**

WORK PLAN

The major tasks and associated periods of activity for this 1-1/2 year study are summarized in table 3..

Table 3. Major work tasks and timelines

Task	04/2011	05/2011	06/2011	07/2011	08/2011	09/2011	10/2011	11/2011	12/2011	01/2012	02/2012	03/2012	04/2012	05/2012	06/2012	07/2012	08/2012	09/2012
Recharge Modeling																		
Prepare input datasets	x	x	x	x	x													
Modify water-budget model code				x	x	X	x											
Run model scenarios and analyze						X	x	x										
Report Preparation																		
Writing								x	x	x	x	x	x					
Review/revise													x	x	x			
Approvals																x	x	
Publication																		x

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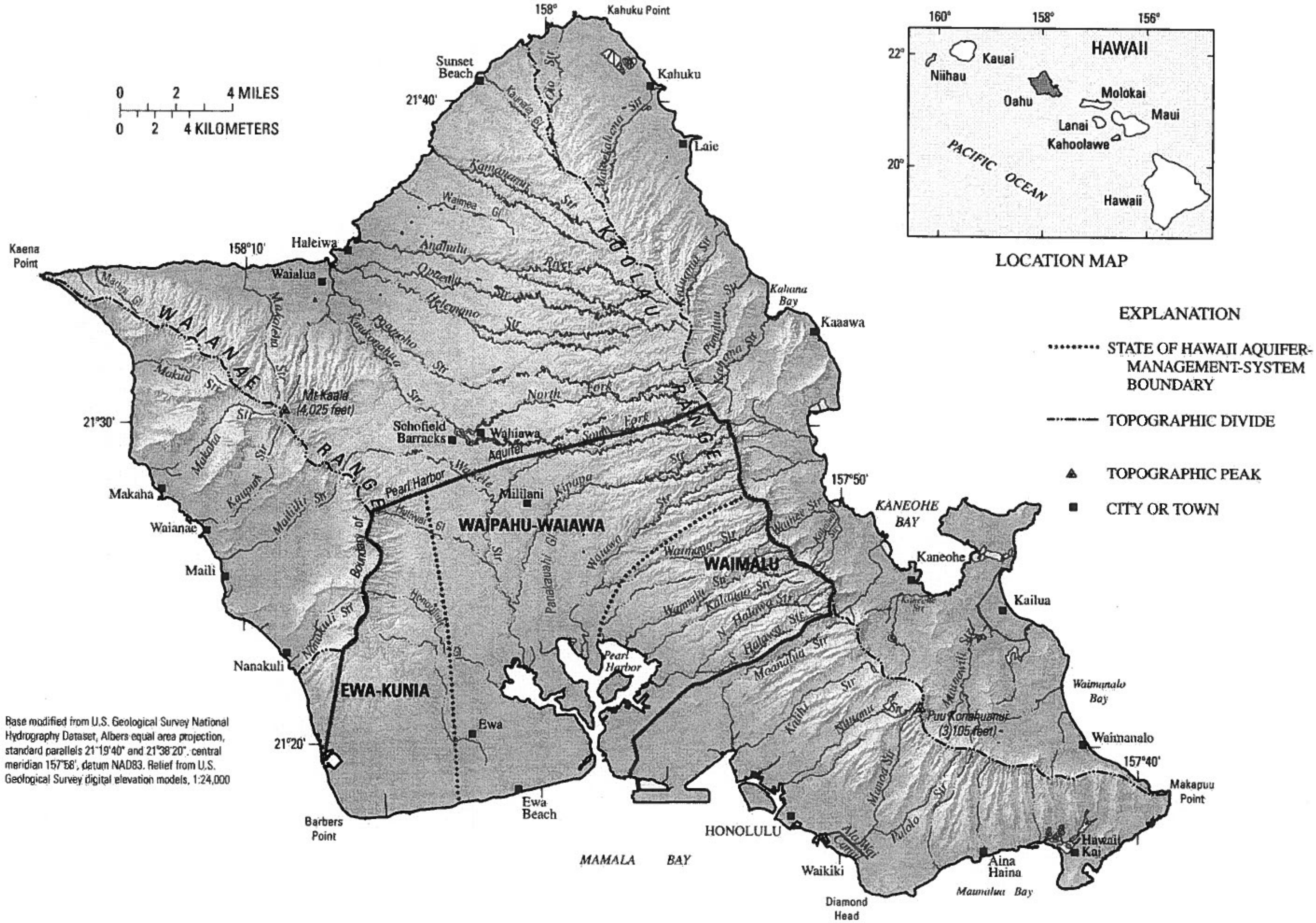

Figure 1. Pearl Harbor aquifer formed by the Ewa-Kunia, Waipahu-Waiawa, and Waimalu management systems and other geographic features, Oahu, Hawaii.

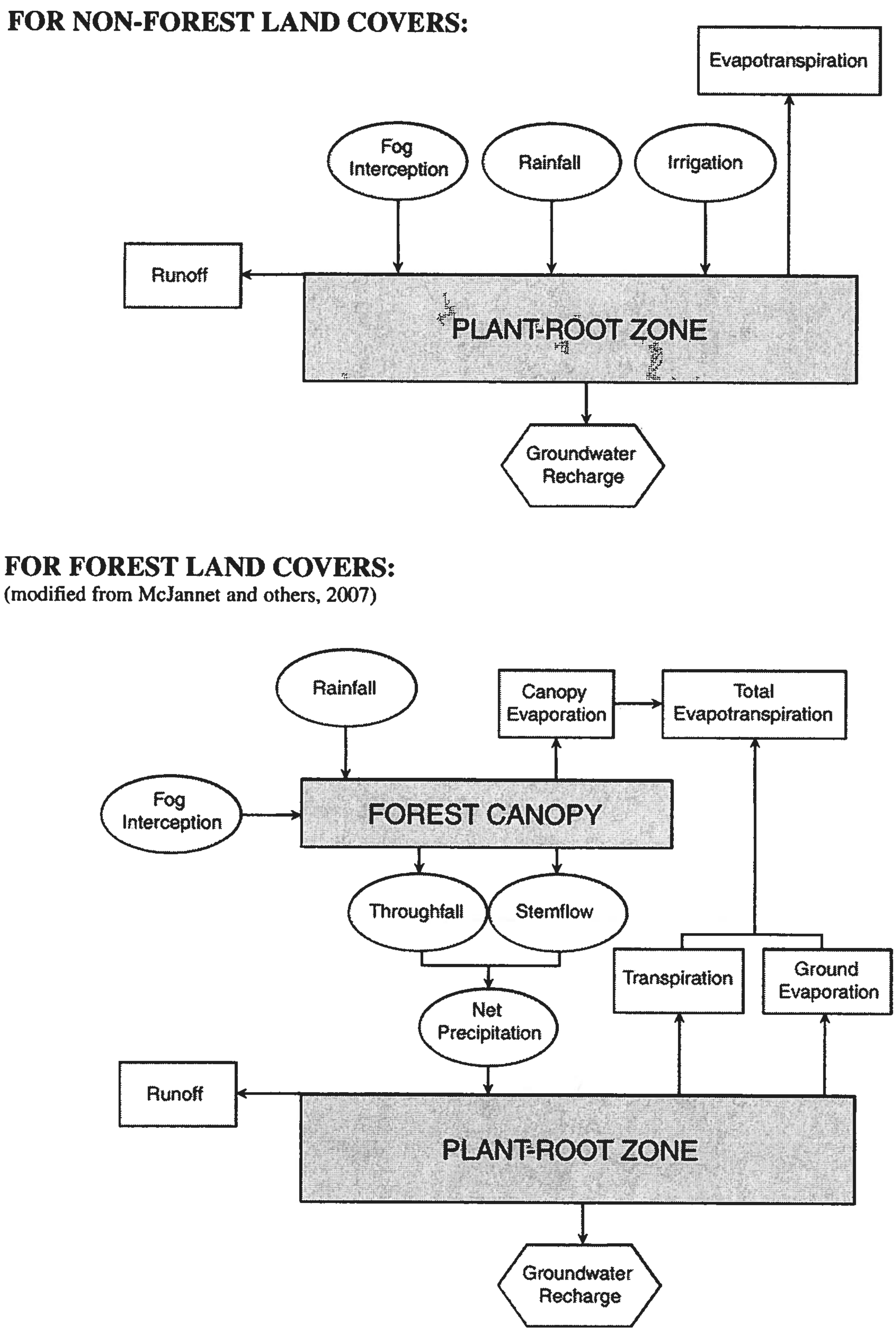

Figure 2. Generalized water-budget flow diagrams for both forest and non-forest land covers.